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Acid Precipitation and Its Effects on Terrestrial and Aquatic Ecosystems

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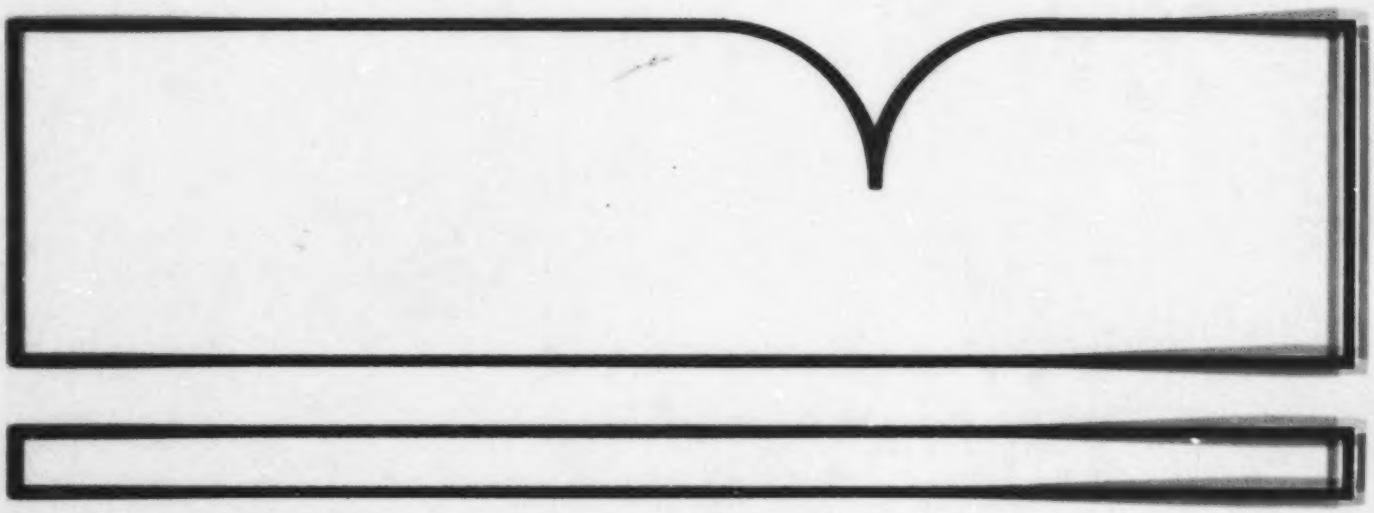

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16. ABSTRACT

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These results show why a National Atmospheric Deposition Program is currently being developed to determine spacial and temporal trends in the amount, chemical form and geographical distribution of atmospheric deposition and its effects on vegetation, soils and aquatic ecosystems.

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ACID PRECIPITATION AND ITS EFFECTS ON TERRESTRIAL AND AQUATIC ECOSYSTEMS

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Introduction

Acid rain is becoming a dominant feature of man-induced change in the chemical climate of the earth. But the increasing acidity of rain is only part of the changing chemistry of precipitation, dry particulate matter, aerosols, and gases. Recent research has demonstrated that (1) atmospheric deposition contains both beneficial nutrients and injurious substances; (2) plants, animals, and ecosystems vary greatly in susceptibility, tolerance, and adaptability to changes in atmospheric deposition; (3) injury is most likely when rapid changes in the chemical climate coincide with the presence of a vulnerable life form or life stage; (4) increasing acidity of precipitation has caused extinction of fish and other changes in species composition at all trophic levels in oligotrophic lakes in northern Europe and eastern North America; and (5) simulated acid rain has caused leaching of nutrients from soil and both direct and indirect injury to terrestrial vegetation. With rare exceptions, however, economic damage to crops by naturally occurring acid rains has not been demonstrated to date.

These results show why a National Atmospheric Deposition Program is currently being developed to determine spacial and temporal trends in the amount, chemical form, and geographical distribution of atmospheric deposition and its effects on vegetation, soils, and aquatic ecosystems.

Acid Precipitation as Part of a General Phenomenon of Atmospheric Deposition

Terrestrial vegetation, soils, and surface waters are the primary deposition sites for all types of substances dispersed in the atmosphere. Most plants take up dissolved nutrients directly from precipitation as well as from the soil solution.[44,49] Fish and other aquatic organisms live in water derived from precipitation but filtered through the soil. Uptake of nutrients from atmospheric sources is especially important in natural ecosystems, such as lakes, estuaries, wetlands, forests, and rangelands, where nutrients from other sources are scarce and where fertilization is not a normal management procedure. But this uptake process also increases the vulnerability of terrestrial and aquatic organisms to injury by acid precipitation and toxic aerosols and gases.[13]

Precipitation formed in an atmosphere relatively free from natural or anthropogenic sources of contamination would have a pH of about 5.6 due to dissolution of gaseous CO_2. Thus, acid precipitation has been defined operationally as rain or snow

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with a pH value below 5.6. But acidity in precipitation must be understood as a reflection not only of the amounts of substances yielding hydrogen ions (such as sulfuric, nitric, hydrochloric, and organic acids) but also of the total ionic balance between all the cations in precipitation.[34,40]

Airborne substances that influence terrestrial plants and animals include: sea spray from oceans and large lakes; dust resulting from wind erosion of soil as well as from volcanic and cosmic sources; gases, such as CO_2, NH_3, SO_2, H_2S, CH_4, H_2, etc., released from decomposing organic matter and volcanoes; biogenic particles, such as spores, hyphal fragments, bacteria, and pollen; particulate matter, aerosols, and gases produced by wild fires and controlled burning of agricultural, forest, and urban wastes as well as from industrial, agricultural, residential, and commercial heating and transportation operations.[3,44]

Combustion of fossil fuels is the largest anthropogenic source of airborne substances.[23] Some of these substances include beneficial nutrient elements; others are injurious to terrestrial and aquatic ecosystems.[39,44,46,49]

Most of the substances dispersed in the atmosphere are at least partially soluble in water. These dissolved substances can be absorbed or assimilated by plants when precipitation is intercepted by vegetation. Since some of the substances dissolved in precipitation are beneficial while others are injurious to plants and animals, the net effect of atmospheric deposition can be beneficial or injurious depending on the chemical composition of the deposited matter, the duration and intensity of deposition episodes, the species and genetic characteristics of the organisms on which the substances are deposited, and the physiological condition, structure, phenology, and stage of maturity of the organisms.[13]

Direct injury to living organisms by acid precipitation is most likely when a particularly vulnerable life form (for example, lichens or fish) is exposed at a particularly vulnerable life stage (for example, the early stages of reproduction), and is growing in a poorly buffered environment (for example, sandy soils or oligotrophic lakes and bogs) during a season of the year when acid precipitation is most likely (for example, spring rains).[13,20]

Rain and snow change in chemical composition within, as well as between, precipitation events. In cold climates, acid substances accumulate in the snowpack, where they are released in concentrated form with the first meltwater and thus cause very sudden increases in acidity of soils, vegetation, and surface waters.[35,36] Thus, a given organism or ecosystem may be subject to beneficial atmospheric influences at one time, and to negative influences at another time, within a given day, month, growing season, or the years of its development in the case of perennial plants and animals.[46] Even a given molecular species, such as SO_2 or NO_2, may be absorbed and utilized as a beneficial nutrient at one concentration; while at another, higher concentration, even on the same day, the same substance may be absorbed and found to be toxic or even injurious to the very same plant, animal, or microorganism.

Herbaceous and perennial plants are subject to changes in atmospheric deposition within their annual cycles of growth. Trees and fish, on the other hand, persist for many years (or even decades in the case of trees); they are subject to long-term, as well as seasonal, changes in the chemistry of the atmosphere and precipitation.

For all of the above reasons, it is difficult to assess the effects of acid substances in precipitation in isolation from the general chemistry of the atmosphere. The effects of

acidic precipitation on terrestrial and aquatic ecosystems are only one facet of the much larger subject of surface interactions of plants with the atmosphere and the soil. The effects of a given "acid rain" or a prevailing condition of "acid rains" are very complex, variable in time, and involve significant interactions that are only partially understood.[20]

Direct and Indirect Effects of Acid Precipitation on Vegetation

A partial list of theoretical effects of acid precipitation on vegetation was developed earlier by Tamm and Cowling[46] and is reproduced in Table 1. The effects are classified as either direct or indirect, although most direct effects will have many indirect consequences as well. A decreased rate of growth would be the expected consequence of most of the effects postulated in Table 1, but unequivocal evidence of significant growth effects has yet to be demonstrated in agricultural, forest, or range ecosystems. Specific biological effects that have been proven to occur in at least one experimental plant are marked with a dot (•) next to the numbers in Table 1.

The Availability of Essential and Injurious Elements from the Atmosphere

Plant life and animal life as we know it would be impossible without atmospheric sources of carbon for photosynthesis, nitrogen for biological fixation and protein synthesis, sulfur for protein synthesis, oxygen for respiration and synthesis of carbohydrates, and water for transpiration within plants. Many essential elements and injurious substances are present in the gaseous, particulate, and aerosol emissions from natural and anthropogenic sources. Essentially all of these diverse emissions into the atmosphere return to the surface of the earth where they are deposited into ecosystems by one of four major processes: (1) wet fallout of substances dissolved or suspended in raindrops or adsorbed on snowflakes; (2) gravitational settling of windblown dust and particulate matter; (3) impaction of aerosols; and (4) absorption of gases. Processes 2, 3, and 4 are component parts of so-called dry deposition.

Many natural ecosystems (both terrestrial and aquatic) are markedly influenced by deposition of nutrient and toxic elements from the atmosphere. Among the essential elements, carbon, hydrogen, and oxygen are rarely limiting. Nitrogen, phosphorus, and potassium are often limiting and, consequently, are added as major fertilizer elements. Sulfur, calcium, and magnesium are sometimes limiting, as are the so-called micronutrients—iron, copper, zinc, manganese, molybdenum, and boron.

Some elements are both essential and injurious to organisms. For example, small amounts of sulfur and large amounts of nitrogen are needed for synthesis of proteins, nucleic acids, and other substances in plants and animals; but gaseous oxides, as well as acids, of sulfur and nitrogen are injurious to many organisms at very low concentrations. Similarly, excess amounts of the micronutrient elements and heavy metals can be injurious. Atmospheric fluoride is toxic to plants at 25–50 ppm. Aluminum is the most abundant toxic metal in the earth's crust. The availability and toxicity of aluminum and other metal ions are influenced greatly by the acidity of

TABLE 1

POTENTIAL EFFECTS OF ACID PRECIPITATION ON VEGETATION*

Direct Effects

●1. *Damage to protective surface structures such as cuticle.*

Damage to surface structures may occur due to accelerated erosion of the cuticular layer that protects most foliar organs. It also could result from direct injury to surface cells by high concentrations of sulfuric acid and other harmful substances that are concentrated by evaporation or adherence of soot particles on plant surfaces.

●2. *Interference with normal functioning of guard cells.*

Malfunction of guard cells will lead to loss of control of stomata and thus to altered rates of transpiration and gas-exchange processes and possibly increased susceptibility to penetration by foliar plant pathogens.

●3. *Poisoning of plant cells after diffusion of acidic substances through stomata or cuticle.*

This could lead to development of deep necrotic or senescent spots on foliar organs including leaves, flowers, twigs, and branches.

●4. *Disturbance of normal metabolism or growth processes without necrosis of plant cells.*

Such disturbances may lead to decreased photosynthetic efficiency, altered respiratory patterns and intermediary metabolism, as well as abnormal development or premature senescence of leaves or other organs.

●5. *Alteration of leaf- and root-exudation processes.*

Such alterations may lead to changes in populations of foliar-surface and root-surface microflora and microfauna, including nitrogen-fixing organisms.

●6. *Interference with reproduction processes.*

Such interference may be achieved by decreasing the viability of pollen, interference with fertilization, decreased fruit or seed production, decreased germinability of seeds, etc.

●7. *Synergistic interaction with other environmental stress factors.*

Such reinforcing interactions may occur with gaseous sulfur dioxide, ozone, fluoride, soot particles, and other air pollutants, as well as drought, flooding, etc.

Indirect Effects

●1. *Accelerated leaching of substances from foliar organs.*

Damage to cuticle and surface cells may lead to accelerated leaching of mineral elements and organic substances from leaves, twigs, branches, and stems.

2. *Increased susceptibility to drought and other environmental stress factors.*

Erosion of cuticle, interference with normal functioning of guard cells, and direct injury to surface cells may lead to increased evapotranspiration from foliar organs and vulnerability to drought, air pollutants, and other environmental stress factors.

●3. *Alteration of symbiotic associations.*

Changes in leaf- and root-exudation processes and accelerated leaching of organic and inorganic substances from plants may affect the formation, development, balance, and function of symbiotic associations, such as mycorrhizae, nitrogen-fixing organisms, lichens, etc.

●4. *Alteration of host-parasite interactions.*

Resistance and/or susceptibility to biotic pathogens, parasites, and insects may be altered by subjecting plants to any environmental stress. Acid precipitation may increase the susceptibility of plants to these injurious agents, alter their capacity to tolerate disease or injury, or alter the virulence of pathogens. The effects of acid precipitation may vary with the following: the nature of the pathogen involved (whether a fungus, bacterium, mycoplasma, virus, nematode, parasitic seed plant, insect, or multiple-pathogen complex); the species, age, and physiological status of the host; and the stage in the disease cycle in which the acidic stress is applied. For example, acid rain might decrease the infective capacity of bacteria before infection and increase the susceptibility of the host to disease development after infection.

*From Tamm and Cowling.[46]

soils, which in turn is influenced by the abundance of acid precipitation. Aluminum ions are toxic to many organisms at concentrations below 1 ppm. Estimates of the threshold concentrations for detectable injury or economic damage by air pollutants, including NO_2, SO_2, O_3, toxic metal ions, and acid precipitation, require substantial additional research with a great variety of organisms and ecosystems.

In earlier decades, it was believed that essential nutrients were taken up by plants almost entirely from the soil. Now, it is recognized that airborne gases, particulate matter, and aerosols significantly augment the supply of both essential and injurious elements.[44] In fact, all of the nutrient elements essential for growth of plants can be taken up readily through foliar organs as well as by absorption by roots from the soil solution.[39,44,49]

Most cultivated crops require large amounts of essential nutrients. For this reason, more nutrients are required for sustained-yield agriculture than for sustained-yield range management or forestry. This is true for rangelands because biomass yields are very low, and for forests because the parts of trees that are usually harvested—the wood and bark of tree stems—contain very much less of most essential elements than do the seeds and fruits that are commonly harvested in agriculture. This is a major reason why soil fertilization is so common in agriculture and so rare in forestry and range management. In some forests and natural grasslands, atmospheric deposition is adequate to permit sustained-yield cropping of the land without fertilization. This is much less likely to remain so, as more and more of the nutrient-rich branches, foliage, and roots of trees are being harvested in so-called whole-tree chipping and other modern forestry practices.

Many scientists believe that acid rain and snow are deposited only onto soils, where acid substances could be neutralized in well-buffered soils or by applications of lime. This is true for some agricultural lands, especially after harvesting of crops. But it is not true for forests, rangelands, or even for most agricultural lands during the growing season. Most raindrops are intercepted by the foliage of plants, where substances dissolved in the rain can induce various physiological changes before reaching the soil. These early effects include erosion of epicuticular waxes and leaching of essential elements and various metabolites from foliar organs. In a mature forest, for example, rain will wash over three tiers of foliage before reaching the soil. Most forests and rangelands in the United States are rarely fertilized and have almost never been limed to neutralize soil acidity. Furthermore, forests cover about half the total land area of North America. Forest trees develop very large canopies of leaves and branches that extend high into the air. Thus, forests provide a very large surface for deposition and assimilation of all the beneficial and injurious substances dispersed in the atmosphere and deposited as precipitation.[44,46,49]

Sources, Amounts, and Distance of Transport of Beneficial and Injurious Substances in the Atmosphere

There are three major reasons why agricultural, range, forest, and aquatic biologists are becoming increasingly concerned about atmospheric transport and deposition of both nutritionally beneficial and potentially injurious substances: (1) vegetation, soils, and surface waters are the primary deposition sites for precipitation and airborne particulate matter of all types; (2) atmospheric deposition constitutes an

important source of nutrients and potentially injurious substances that affect the productivity and stability of agricultural, forest, and aquatic ecosystems;[45] and (3) human activities are steadily increasing the amounts and variety of substances dispersed in the atmosphere.[3,21,25,33]

Previously, it was believed that most anthropogenic emissions were removed from the atmosphere near the site of emission. Now it is recognized, particularly with increased use of tall stacks in power plants, that atmospheric processes can lead to extensive mixing, which leads to both chemical and physical interactions and transformations of atmospheric particles, aerosols, and gases. Furthermore, these substances and their reaction products are dispersed by meteorological processes and finally enter the biosphere in fields of deposition that extend hundreds or even thousands of kilometers from the original sources of emission. The fallout of radioactive materials all over the Northern Hemisphere since the early 1950s as the result of atomic bomb tests provides a dramatic and continuing reminder of the long-distance transport and deposition of pollutants.

TABLE 2

BIOGEOCHEMICAL AND TECHNOLOGICAL FORCES IN THE BIOSPHERE OF THE EARTH*

Biosphere Components	Tons per Year
Biogeochemical Processes:	
Yield of photomass	1×10^{10}
Cycle of inorganic elements	1×10^{10}
River discharges:	
Dissolved substances	3×10^{9}
Suspended substances	2×10^{10}
Anthropogenic Sources:	
Output of fertilizers	3×10^{8}
Industrial dust	3×10^{8}
Garbage, urban wastes and by-products	2×10^{10}
Mine refuse	5×10^{9}
Aerosols and gas discharges	1×10^{9}

*Data of Kovda.[25]

The amounts of various substances introduced deliberately or inadvertently by man into the biosphere of industrialized regions of the earth are becoming so large that man is becoming a major force in the biogeochemistry of these regions.[25] TABLE 2 contains a tabulation of data on annual output of fertilizers, industrial dusts, garbage and other urban wastes and by-products, mine refuse, and discharges of aerosols and gases mainly from combustion of fossil fuels. All of these categories of matter are becoming comparable in magnitude with the discharges of dissolved and suspended substances in all the rivers of the world, the annual yield of photosynthetic products, or the cycling of inorganic elements in the earth as a whole. Anthropogenic emissions into the atmosphere are also very large, as shown in TABLE 3. Most gases, carbon oxides, and aerosols result from combustion of fossil fuels. A very large fraction of these global emissions was produced in the United States.

If the United States is to so greatly augment the amounts of substances dispersed in the atmosphere and deposited into the biosphere of the earth, it is essential that we should measure the amount and chemical form of the deposited matter and

TABLE 3

ANTHROPOGENIC EMISSIONS INTO THE ATMOSPHERE*

Type of Emission	Tons per Year†
Dust	2.5×10^8
Gases (mainly SO_2, HC, and NO_x)	6.5×10^8
Carbon oxides ($CO + CO_2$)	2.0×10^9
Aerosols	1.0×10^9

*Data of Kovda.[25]
†Doubling about every 7–10 years.

understand the biological consequences of that deposition in our country and abroad.

Regrettably, our understanding of these processes in North America is very fragmentary. Fortunately, however, more extensive measurements of atmospheric deposition and its biological consequences have been made in Europe, where an atmospheric deposition network has been maintained since the late 1940s.[33]

The European Air Chemistry Network began in Sweden in 1952 and has gradually spread to include most of western Europe and parts of eastern Europe, including Poland and the Soviet Union.* Since the mid 1950s, a network of about 100 stations has provided monthly measurements of changes in the chemistry of precipitation and of the air at ground level. The substances analyzed at most of these stations include the following major cations and anions: NH_4, Na, Ca, K, Mg, SO_4, NO_3, HCO_3, and Cl, as well as pH, conductivity, and, more recently, titratable acidity and alkalinity. These data have shown long-term trends in the chemistry of precipitation. For example, the amount of nitrate nitrogen in precipitation (an important fertilizer element) increased markedly in many parts of Europe during the 15 years between 1955 and 1970.[34] Nitrate nitrogen helps plants grow. Thus, the nitrogen added in precipitation probably increased yields of agricultural and forest crops. A similar trend between the 1920s and the 1970s has been measured at Ithaca, New York.[26]

But not all the substances detected in precipitation are beneficial. Long-term trends of injurious sulfate and hydrogen ions also have been detected.[21] These changes are attributed to strong acids formed in the atmosphere, mainly from oxides of sulfur and nitrogen produced during combustion of fossil fuels. More recent data show that these trends of increasing acidity are continuing,[2,33,34] although the relative contribution of sulfuric and nitric acids is changing.[26]

SPATIAL AND TEMPORAL CHANGES IN THE CHEMISTRY OF PRECIPITATION IN NORTH AMERICA

Some monitoring of the chemistry of precipitation has also been carried on in the United States.[10,14,27] Some of these studies provide excellent and reliable information about spatial variability in the acidity of precipitation. But most studies in this country

*A list of publications based on the European Air Chemistry Network can be obtained from the International Meteorological Institute, Stockholm, Sweden.

have suffered from three major shortcomings: (1) the data were collected for a limited land area—typically, only a single point or a few points in one or two states;[14] (2) the data were collected for very limited periods of time—typically, only 1 or 2 years; and (3) very few direct measurements of pH were made. There is only one location in the United States—the Hubbard Brook Experiment Forest in New Hampshire—where the acidity of rain has been measured directly and consistently for more than 10 years. The longest-term national monitoring program was operated by the National Center for Atmospheric Research for 6 years from 1960 to 1966.[27]

Using fragmentary bits of information, obtained indirectly and in limited areas and periods of time, Cogbill and Likens[5] managed to calculate the probable changes in average acidity of rainfall in various parts of the eastern United States from 1955–1973. As shown in FIGURE 1,[26] precipitation in a large portion of the eastern United States was less than pH 5.6 in 1955–56; the region of greatest acidity (lowest pH) was generally consistent with the region where sulfur emissions were high—parts of Ohio, Pennsylvania, West Virginia, New York, and New England. By 1972–1973, however, the area with an average rain pH of below 4.5 had extended to include parts of Missouri, Arkansas, Mississippi, Alabama, Georgia, South Carolina, North Carolina, Virginia, Kentucky, Illinois, Michigan, and farther north into New England and Canada. Essentially, it embraced most of the area east of the Mississippi River. Individual rainstorms with pH values below 3.6 have been reported in New York, Illinois, Indiana, New Hampshire, Massachusetts, and North Carolina—in some cases, many hundreds of kilometers from major sources of air pollution.[26]

The relative contribution of sulfate and nitrate to the total acidity of precipitation apparently has changed markedly during the years since 1964–65. At Hubbard Brook, New Hampshire, the ratio of sulfate to nitrate ions changed from 5.5:1 in 1964 to 2.2:1

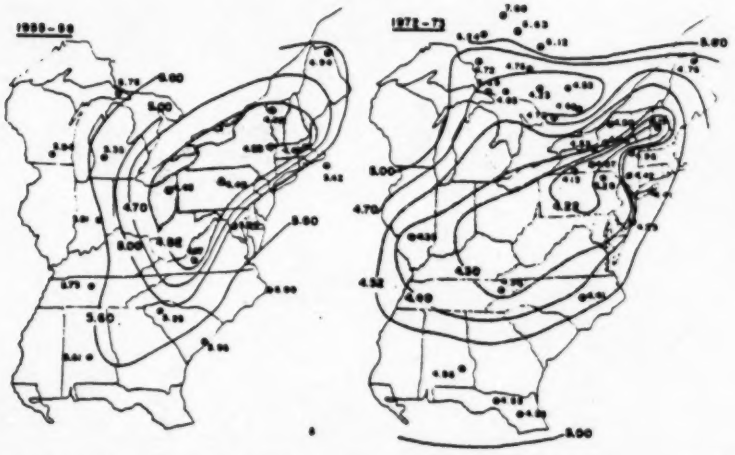

FIGURE 1. Changes in the weighted annual average pH of precipitation in the eastern United States in 1955–56 and 1972–73. Adapted from Likens[26] and used by permission of *Chemical and Engineering News*.

in 1974. During this same decade, the total input of hydrogen ions increased by 36%. Thus, most of this increase appears to be due to increased amounts of nitric acid.[26]

Effects of Acid Precipitation on Ecosystems

Research on the effects of change in the chemistry of precipitation on terrestrial and aquatic ecosystems has been conducted in Europe since about 1955 and in North America mainly since about 1966. Several publications are worthy of special note in this connection. The pioneering and outstanding research by Eville Gorham—first in England, later in Canada, and most recently in the United States—dealt with effects on lake waters, aquatic vegetation, terrestrial vegetation and human health.[15,16] Svante Odén published his famous Ecological Committee Report in 1968.[33] In 1971, Bolin and coworkers completed a case study about sulfur deposition and acid precipitation in Sweden, as a contribution to the United Nations Conference on the Human Environment.[3] In 1972, the Norwegian government established a special multiinstitute research project called Acid Precipitation: Effects on Forests and Fish, with an annual budget of about 10 million kroner (about $2 million).[43] This huge project was initiated with two specific objectives:

1. To establish as precisely as possible the effects of acid precipitation on forests and freshwater fish; and
2. To investigate the effects of air pollutants on soil, vegetation, and water, to the extent required to support the primary objective.

The First International Symposium on Acid Precipitation and the Forest Ecosystem was held at The Ohio State University at Columbus in May of 1975.[8] In June of 1976, the International Conference on Effects of Acid Precipitation was held at Telemark, Norway, and the major papers assembled for this meeting were published by Braekke *et al.*[4] and in a special issue of *Ambio*.[2] In November 1976, Likens published his summary report in *Chemical and Engineering News*.[26] In 1977, the Organization for Economic Cooperation and Development[37] published their comprehensive findings regarding the international exchange of sulfur compounds among the various nations of Europe. In May 1978, a NATO Advanced Research Institute on Ecological Effects of Acid Precipitation was held at Toronto, Canada. In September 1978, the Central Electricity Generating Board in England hosted an international symposium on the biological effects of acid precipitation. The proceedings of these last two meetings are scheduled for publication in 1979 and 1980, respectively.

Effects on Aquatic Ecosystems

The effects of acid precipitation on fish populations and aquatic ecosystems have been very pronounced in various regions of northern Europe and eastern North America.[7] The most important of these effects were summarized at the First International Symposium on Acid Precipitation and the Forest Ecosystem[8,9] and at the International Congress on the Effects of Acid Precipitation held at Telemark, Norway, in June 1976.[2] The latter report reads in part:

> Water quality has changed during the last decades in numerous lakes and rivers in southern Scandinavia and eastern North America, pH often falling below 5, with sulfate

becoming the most important anion. There is strong evidence that this change is due to acid precipitation. It is associated with the loss of buffering capacity, and the occurrence of additional short-term decreases in pH, related to meltwater from snow or episodic inputs of acid precipitation from polluted air masses.

The acidification of freshwater ecosystems leads to many changes, most of which involve decreases in biological activity and important changes in nutrient cycling. For example, decomposer organisms are less active in acid waters, resulting in increased accumulations of organic matter. When the pH drops below 6, numbers of species in several groups of organisms (phytoplankton and zooplankton, bottom fauna and several other groups of invertebrates), decrease considerably, thus affecting the variety of food for fish and other animals depending on freshwater ecosystems. Shifts have been observed from higher aquatic plants toward mosses, and this will influence not only the bottom fauna but also nutrient exchange with the sediments.

High acidity (pH <5.5) seriously affects fish populations, particularly when occurring in waters of low ionic strength. Rapid extinction rates of fish populations inhabiting acidified waters have been observed during the past few decades in southern Scandinavia as well as in parts of eastern North America.

Case studies of several fish populations and experiments clearly indicate that the elimination of fish is often a result of chronic reproductive failure in acid conditions and of damage done to sensitive stages, especially the newly hatched larvae. Such a process is insidious and not readily evident in terms of fishery yield until extinction is imminent.

In lakes and streams with soft waters, acid stress has also been shown both experimentally and in field studies to cause mortality among adult fish as a result of interference with physiological mechanisms regulating active ion exchange across gill membranes. In this case factors such as size, age, acclimation history, genetic background and ionic strength of the water interact in complex ways to determine the relative acid tolerance of the fish.

There is strong evidence that the increased acidity of precipitation is now the main cause of these extensive losses of salmonid fish stocks as well as other populations of economic importance both in southern Scandinavia and the northeastern part of the United States and parts of southeastern Canada.

Sensitivity is related to the tolerance of the differing species (reflecting their genetic diversity), to the timing of episodic acid precipitation in relation to the stage in the life cycle, and to the influence of the geological environment, e.g., lakes and rivers on bedrock, overburden and soils highly resistant to chemical weathering. This may also be the case in geological areas of this type elsewhere in the world. Special consideration should be given to the preservation of unique gene pools and habitats.

There may be complex interactions with other environmental factors, including some organic compounds. In waters of low pH the adverse effects of heavy metals on fish and other organisms can be enhanced, whereas at pH values nearer neutrality these substances would have been tolerated.[2]

Effects on Terrestrial Ecosystems

Effects on terrestrial ecosystems generally have been less well documented than those on populations of freshwater fish and other aquatic organisms. Nevertheless, certain definite effects have been reported. The most striking of these effects was development of peat moss (*Sphagnum* sp.) as a submarine, rather than a terrestrial, plant in acidified lakes and streams in Sweden.[17] Dense mats of *Sphagnum* and an apparently parasitic aquatic fungus develop on the bottom of these lakes in water as deep as 18 meters. This growth induces oligotrophication (opposite of eutrophication)—a self-accelerating process that leads to a substantial nutrient-impoverishment of lake waters.

Analyses of forest growth in southern Sweden from 1896 to 1965 showed a 2 to 7% decrease in growth between 1950 and 1965. Johnsson and Sundberg[23,43] "found no

good reason for attributing [this] reduction in growth to any cause other than acidification." Similar attempts to quantify possible effects on growth of forests in the United States have been inconclusive.

Other reports given at the meetings in Columbus, Ohio, and Telemark, Norway, indicated that:

1. Forest canopies filter out sulfur and hydrogen ions from precipitation;[24,29]
2. Acidity of bark and development of cuticular features, such as frequency and size of stomata, can be used as biological indicators of sulfur pollution and acidification;[41] for example, pH values of 2.2 to 4.7 were reported in the bark of several species of trees in Poland;[5]
3. Vegetation developing in recently formed sandy soils or glacial outwash areas is more vulnerable to the effects of acid precipitation than is vegetation growing in older, well-buffered soils of high clay content and consequently large base exchange capacity;[12,47]
4. Before reaching the soil, acidic substances in precipitation can induce changes in the physiology of foliar organs;[46]
5. After reaching the soil, these substances also can induce changes in root function and in the availability of essential cations;[12]
6. Ammonia and other cations combine with sulfate ions in the atmosphere and tend to neutralize and thus hide atmospheric acidity—when the cations are absorbed by plants, however, additional hydrogen ions are released by the plants and contribute to the further acidification of agricultural and forest ecosystems;[34]
7. Acid rains increase the leaching of nutrient cations from the root zone of plants;[32,38]
8. Acid precipitation also increases the solubility (and therefore the toxicity) of metals, such as Al, Pb, and Hg, in soil.[30]

Simulated "rain" acidified with sulfuric acid has been reported to:

1. Induce direct injury to foliage of pines, birch, and mosses;[42,47,51]
2. Induce symptoms similar to those caused by certain other pollutants and biotic pathogens;[50]
3. Induce poorer germination of spruce seeds;[1]
4. Accelerate leaching of nutrients from foliage[1,51] and from soil;[1,28,48]
5. Inhibit decomposition of leaf litter from the forest floor;[1]
6. Increase erosion of epicuticular waxes on oak and bean leaves;[42]
7. Decrease uptake of nitrogen by endomycorrhizae of sweetgum seedlings;[19]
8. Inhibit reproduction of root-knot nematodes;[42]
9. Inhibit development of bean rust and production of telia by the oak-leaf-rust fungus, *Cronartium fusiforme*;[42]
10. Inhibit or stimulate development of halo blight in bean seedlings, depending on the time in the disease cycle during which the simulated "rain" was applied;[42] and
11. Inhibit nodulation and fixation of nitrogen by *Rhizobium* in bean and soybean seedlings.[42]

As yet unknown constituents of precipitation have been shown to induce

"russetting"—brown blemishes that decrease the market quality and price of yellow delicious apples.[32]

With the exception of this latter effect on apples, the possible economic consequences of the various biological effects listed above are not known. Nevertheless, the variety of biological influences that have been observed suggests that (1) much more research is needed to evaluate the ecological and possible economic influences of changes in the acidity and other chemical properties of precipitation; and (2) a well-coordinated network to measure long-term changes in the chemistry of air and precipitation is needed in rural and urban areas throughout North America.

Based on a general analysis of effects reported to date, Heck *et al.*[20] offered the following generalizations about the relative vulnerability of various organisms and ecosystems to acid precipitation:

1. Freshwater fish are more vulnerable to acute acid shock than is freshwater vegetation;
2. Aquatic vegetation is more vulnerable than terrestrial vegetation;
3. Herbaceous vegetation is more vulnerable than woody vegetation;
4. Plants growing in recently formed sandy soils or glacial outwash areas are more vulnerable than plants growing in well-buffered soils of high clay content and consequently large base exchange capacity;
5. Reproductive stages are more vulnerable than vegetative stages;
6. Plants growing in natural ecosystems are more vulnerable than plants growing in agroecosystems where liming and other fertilization practices are common;
7. Coniferous forests are more vulnerable than hardwood forests; and
8. Plants growing in regions of high rainfall are more vulnerable than desert plants.

Development of a National Atmospheric Deposition Program for the United States

In 1975, the National Academy of Sciences Committee on Atmospheric Sciences published its report on *Atmospheric Chemistry: Problems and Scope*.[31] In May of 1975, a workshop to define future needs for research on acid precipitation was held immediately following the First International Symposium on Acid Precipitation and the Forest Ecosystem. The recommendations of this workshop were published by Dochinger and Seliga.[9] In May 1977, the director of the Norwegian Special Project on Acid Precipitation provided an updated analysis of research needs on acid precipitation as perceived from the standpoint of knowledge of acid precipitation effects in Scandinavia.[43] In September 1978, the Federal Interagency Advisory Committee on Water Data completed its report on *Research and Monitoring of Chemistry in the United States: Present Status and Future Needs*.[22] In September 1977, the congressionally mandated "Committee of Nine," responsible for regional research in the agricultural experiment stations of the United States, approved plans for establishment of a long-term interagency research project designated NC-141, Chemical Changes in Atmospheric Deposition and Effects on Agricultural and Forested Land Surface Waters in the United States.[6] In March of 1978, the Fish and Wildlife Service published their extensive analysis of impacts of coal-fired power plants (including acid

precipitation) on fish, wildlife, and their habitats.[11] In November 1978, the name of the NC-141 program was changed to the National Atmospheric Deposition Program (NADP); and in December 1978, a subcommittee of NADP completed a report to the President's Council on Environmental Quality entitled *A National Program to Assess the Problem of Atmospheric Deposition (Acid Rain).*[13]

In each of these major studies, the need for action to increase research on the changing chemistry of precipitation and its ecological effects was described. A remarkable degree of similarity in research recommendations is evident in all of these reports: (1) establish a permanent network to continously monitor changes in the chemistry of precipitation, and (2) coordinate this long-term monitoring program with research to determine the sources, transport, and transformation of pollutants, the meteorology of their dispersal and deposition, and the nature and magnitude of their ecological effects on agricultural land, forested land, rangeland, urban lands, and aquatic ecosystems.

An adequate program of monitoring and research ideally should include the various state agricultural experiment stations, the regional forest experiment stations of the Forest Service, and the Agricultural Research Division of the Department of Agriculture, as well as pertinent units of the United States Geological Survey, the Department of Energy, the National Oceanic and Atmospheric Administration, the Environmental Protection Agency, the Tennessee Valley Authority, the National Center for Atmospheric Research, the National Science Foundation, and the National Aeronautics and Space Administration. An effective program will also require the interest and expertise of many scientists in a diverse array of publicly and privately supported colleges and universities in the United States and Canada.

The design for such an integrated, multinational, multidisciplinary, and multi-agency program of research and monitoring has been developed[13] and endorsed by President Carter in his Second Environmental Message.[53] This Presidential Initiative on Acid Rain calls for a research investment of $10 million per year for 10 years and will include each of the following elements:

1. Quantitative analysis of emissions, chemical transformations, and transport and deposition processes;
2. Measurement of spatial and temporal trends in atmospheric deposition in various regions of North America;
3. Analysis of the effects of atmospheric deposition on water quality, vegetation, soils, fish, microorganisms, and simple synthetic ecosystems;
4. Calibrated watershed studies to provide an understanding of the chemical linkages between the atmosphere and both terrestrial and aquatic natural ecosystems; and
5. Economic assessment and criteria development.

As Galloway and his colleagues[13] have emphasized: "The time has come to stop talking and to implement a comprehensive and well-coordinated program of research and monitoring. The United States already lags well behind other nations (including Canada, Norway, and Sweden) despite the severe threat posed by acid precipitation to large areas of this country."

Let's get on with the job!

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